TITLE OF THE INVENTION

CONTROL APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of priority from the prior Japanese Patent Application No. 2000-178535, filed June 14, 2000, the entire contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a control apparatus applied to a speed control or a position control in an industrial robot, a numerical control (NC) machine, a head track seeking of a disk drive or the like.

2. Description of the Related Art

In general, a servo mechanism using a servo actuator has been widely utilized in a position-to-position high speed positioning control or a high speed tracking control for an industrial robot, a NC machine and the like, and a head track seeking or the like for a hard disk drive or a floppy disk drive used in a data processing unit. In the servo mechanism, a high speed response is one of very important conditions for such a control as a speed control, a positioning control or the like.

Now, in a control apparatus which controls

an object including a servo mechanism having various transfer functions of secondary delay, it has been known that the settling time becomes a minimum time, when a critical damping wherein a damping coefficient of a control system constructing a control apparatus becomes 1 is made under a condition that an overshoot does not occur. That is, in a conventional control system constructed by an inner loop for a negative feedback of an output and another inner loop for negative-feeding back the product of the differential value of the output and a gain, the settling time may be set to be minimum by setting the gain in the another inner value in a proper value. Namely, the response of the control system of the conventional control apparatus is expressed by the following differential equation (1).

$$(d^2x/dt^2)+\{(J+k1)/JT\}\cdot(dx/dt)+(1/JT)\cdot x = (1/JT)r \tag{1}$$

where J is a constant, T is a time constant, and k1 is a gain.

Therefore, the gain k1 can be set such that the damping coefficient $\xi = J+k1/2\sqrt{JT} = 1$ is obtained. However, when the damping coefficient ξ exceeds 1, the response becomes slower, so that the settling time is prolonged. Also, when the damping coefficient ξ becomes less than 1, the response becomes faster but vibrating even when an overshoot is allowed, so that

much improvement can not be obtained.

Accordingly, in a field that the settling time is set to be shorter than that at the time of the critical damping and the high speed response is required, a new control approach is required. In a case that such a control system is constituted on the basis of the following equation (2),

$$(d^2e/dt^2)+\{(2\xi Wn) / (1+|e|)\}\cdot(de/dt) + Wn^2e = 0 \quad (2)$$

where Wn is natural frequency and e is deviation, and it is considered that, when the deviation between the input value and the output value is large, a control is conducted so as to approach to a steady state by reducing an apparent damping coefficient $\xi' = \xi/(1+|e|)$ to make the response fast but, when the deviation e becomes small, a control is conducted so as to suppress an overshoot by increasing the apparent damping coefficient. However, according to this approach, there is a problem that, since the response is expressed by a nonlinear differential equation, when the deviation becomes large even in a case of $\xi = 1$ in the equation (2), an overshoot occurs.

An object of the present invention is to provide a control apparatus which reduces the settling time largely without occurrence of an overshoot and which achieves a high speed response.

BRIEF SUMMARY OF THE INVENTION

According to an aspect of the invention, there is provided a control apparatus which controls a controlled system with a transfer function regarded as a secondary delay system. The control apparatus comprises an outer loop for a negative feedback of an output $\underline{x}$ of the controlled system in order to obtain an error $\underline{e}$ between the output $\underline{x}$ and a desired value $\underline{r}$; a first inner loop for a negative feedback of a signal $k1\cdot(dx/dt)$ obtained by multiplying a differential value (dx/dt) of the output $\underline{x}$ of the controlled system by a gain k1 to the deviation $\underline{e}$; and a second inner loop for a positive feedback of a signal of $k2(dx/dt)\cdot|e|$ or $k2(dx/dt)\cdot|e|^n$ to the error $\underline{e}$, using the differential value (dx/dt) and the product obtained by multiplying an absolute value $|e|$ of the deviation $\underline{e}$ or n-th power (n: integer) of the absolute value $|e|$ by a gain k2.

According to the above configuration based on an aspect of the present invention, if the gains k1 and k2 are set so as to meet a predetermined conditional expression of damping coefficients of a control system which are zero and positive, the settling time can be reduced largely and a high speed response can be achieved without occurrence of an overshoot even in a control system having a controlled system with a transfer function regarded as an secondary delay.

Additional objects and advantages of the invention

will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out hereinafter.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate presently preferred embodiments of the invention, and together with the general description given above and the detailed description of the preferred embodiments given below, serve to explain the principles of the invention.

FIG. 1 is a block diagram of a control apparatus according to an embodiment of the present invention;

FIG. 2 is a graph showing the step response of the control system of n = 1 in speed control of an AC servo motor of 500W;

FIG. 3 is a graph showing the relationship between a desired value r and a gain k2 under the same conditions as those in FIG. 2;

FIG. 4 is a graph showing the relationship among the gains k1, k2 and a settling time at a time of the set point r = 6000 rpm;

FIG. 5 is a graph showing the relationship between the gains k1 and k2 for performing the setting without

overshooting;

FIG. 6 is a graph showing a step response of the control system of n = 2 in speed control of an AC servo motor of 500W;

FIG. 7 is a block diagram of the control apparatus according to another embodiment of the present invention; and

FIG. 8 is a block diagram of the control apparatus according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention will be explained below with reference to the drawings.

FIG. 1 shows a control apparatus according to the embodiment of the present invention and applied to a speed control system having the controlled system regarded as a second order system. In, for example, a servo mechanism using a servo actuator, a speed control system having an inertia moment or a mass wherein a torque or a thrust generator is approximated with the first order lag element, a position control system wherein a speed controller is approximated with the first order element, or the like is exemplified as a controlled system regarded as the second order system.

This control apparatus comprises a multi-closed loop control system. In other words, the control apparatus comprises an outer loop 2, an inner loop 4

and a nonlinear inner feedback loop 10. The outer loop 2 executes a negative feedback of an output from a controlled system 1, and includes a deviation computing unit 3 which computes the deviation between a desired value r and a controlled variable, namely the output x which is the signal of the outer loop 2. The inner loop 4 executes a negative feedback of the product between a differential value of the controlled variable, namely the speed x and a gain k1, that is, a compensation signal to a transient change.

A compensation unit 5 performs such a processing that the deviation from the deviation computing unit 3 is cancelled by the compensation signal from the inner loop 4, and a nonlinear inner feedback loop 10.

The inner loop 4 comprises a computing unit 6 having a laplace operator s which takes out the differentiated output of the controlled variable or the output x of the controlled system 1 and a gain multiplier 7 which multiplies a proper gain k1 to the differentiated output from the computing unit 6 for a feedback. The inner loop 4 generates the compensation signal for the transient change of the controlled variable or the output x. Incidentally, J in the transfer function of the controlled system 1 is an inertial moment, T is a time constant, and s is a laplace operator unit.

Such a control apparatus can control the output

of the controlled system 1 to a transient change by setting the gain k1 multiplied to the differentiation of the controlled variable, namely output $\underline{x}$ of the controlled system 1 properly using the inner loop 4 to conduct compensation through a feedback.

The nonlinear inner feedback loop 10 forms an inner positive feedback loop comprising a laplace operator unit 11, an absolute computing unit 12, a gain computing unit 13, and a positive feedback unit 14. The laplace operator unit 11 outputs the differential value of the controlled variable, namely speed $\underline{x}$ of the controlled system 1, The absolute computing unit 12 computes the absolute value of the deviation $\underline{e}$(r-x) obtained by the deviation computing unit 3 or n-th (n=1, 2, 3, ···) power of the absolute value. The gain computing unit 13 multiplies the computation output of the computing unit 12 by a gain k2. The positive feedback unit 14 executes the positive feedback of the product of the output of the gain computing unit 13 and the differential value of the controlled variable or speed x to the compensation unit 5. The nonlinear inner feedback loop 10 serves so as to change the damping coefficient ξ of the control system according to the deviation $\underline{e}$ from the deviation computing unit 3.

Meanwhile, the inner loop 4 performs the negative feedback of the product of the speed differentiation and the gain and it plays a roll for determining

a damping coefficient at a time of a steady state. Therefore, the response of the control system shown in FIG. 1 is expressed by the following differential equation (3).

$$(d^2x/dt^2)+\{(J+k1-k2\cdot|r-x|^n)/JT\}\cdot(dx/dt)+(1+JT)\cdot x=(1/JT)r \qquad (3)$$

The damping coefficient is represented in the following equation (4).

$$\xi^*=[(J+k1-k2|r-x|^n)\ /\ 2(JT)^{1/2}] \qquad (4)$$

Now, $\xi^* \geqq 0$ is assumed from the equation (4) regardless of the controlled variable, namely speed <u>x</u> of the controlled system 1. That is, when the desired value <u>r</u>, and the gains k1 and k2 are determined under such conditions that $J+k1-k2\cdot|r|^n \geqq 0$ is met in the equation (4), the settling time can be reduced without any overshoot.

FIG. 2 shows a step response of the speed control system using an AC servo motor of 500 W ($J = 0.1 \times 10^{-3}kgm^2$, T=10ms) and n=1. Particularly, FIG. 2 shows the step response obtained when k1 is set to be $\xi^*=1$ in a steady state, and for the desired set value <u>r</u> the gain k2 falling in a range in which any overshoot does not occur are set. FIG. 3 shows the relationship between the step desired value <u>r</u> and the gain k2.

Also, for example, in a case of J+k1 = c, when the condition of $c-k2|r| \geqq 0$ is met according to $\xi^* \geqq 0$ shown with the equation (4), a step response having

a settling time shorter than that in a conventional second order control system can be obtained without any overshoot. In FIG. 3, the section which is defined below a solid line is an area wherein any overshoot does not occur. Incidentally, it has been confirmed that, in a case of the gain coefficient $k2 = c/|r|$, improvement in settling time can be maximized.

Regarding a rated set point (3000 rpm), when the present speed control system is set to $k2 = 3 \times 20^{-5}$ and the damping coefficient $\xi = \xi^* = 1$ in the steady state by changing the damping coefficients, the present speed control system can be improved 70% in the settling time in comparison with the conventional speed control system of the damping coefficient $\xi = 1$.

Furthermore, when the gain k1 is set so as to meet the damping coefficient $\xi = \xi^* \geqq 1$ in the steady state and the gain k2 is set so as to meet the condition of $J + k1-k2|r| \geqq 0$, the control system with the condition thus set can further reduce the settling time when compared with the control system of the damping coefficient $\xi = \xi^* = 1$.

Also, when the desired value $\underline{r}$=6000 rpm is set, the gains k1, k2 and the settling time have the relationship shown in FIG. 4 and the relationship is graphically represented as shown in FIG. 5. From these figures, the relationship among the desired value $\underline{r}$, and the gains k1 and k2 meets $J+k1-k2 \cdot |r| \fallingdotseq 0$.

Accordingly, this control system achieves the settling time of 1/10 or less so that its settling time can further be reduced as compared with the conventional control system of the damping coefficient $\xi = 1$.

Next, in a control system where n = 2 is set in the nonlinear inner feedback loop 10, the damping coefficient is expressed by the following equation (5).

$$\xi^* = \{(J+k1-k2|r-x|^2)\}/2(JT)^{1/2} \quad (5)$$

When the desired value <u>r</u>, and the gains k1 and k2 are set so as to meet the condition of $J+k1-k2 \cdot r^2 \geqq 0$, the response can be improved without overshoot and the settling time can be made smaller than that of the control system of n=1. FIG. 6 shows a step response obtained when r=3000 rpm and $k1 = 1.9 \times 10^{-3}$ are set and the gain k2 is changed. The settling time of this control system is improved as compared with the control system of n=1 and the degree of the improvement can achieve about 50 %.

FIG. 7 shows a control apparatus according to another embodiment of the present invention.

This embodiment is a control apparatus for a position control system wherein the controlled system 1 is replaced with the controlled system 1a of a position control model of 1/Js(1+Tps) and an adjusting element 21 which sets the gain k2 to $K2=c/|r|^n (c=J+k1)$ under the desired value <u>r</u> is provided. As the other elements or configuration parts in this embodiment are similar

to those in FIG. 1, like parts are denoted by like reference numerals in FIG. 1 and detailed explanation thereof will be omitted.

Since this control apparatus comprises to be similar to that in FIG. 1, the relationship equation of the desired value r, and the gains k1 and k2 results in $c-k2\ |r|^n = J+k1-k2\ |r|^n \geqq 0$, so that overshoot is prevented from occurring and the settling time can be reduced like the case in FIG. 1.

FIG. 8 shows a control apparatus according to still another embodiment of the present invention. This control apparatus is provided with a control system where a gain K is applied to the controlled system 1, and a gain multiplier 22 having a loop gain kf is added to the outer loop 2 which feeds back the controlled variable, namely speed x from the controlled system 1. As the other elements or configuration parts in this embodiment are similar to those in FIG. 1, like parts are denoted by like reference numerals in FIG. 1 and detailed explanation thereof will be omitted.

The differential equation showing the response of this control system results in the following equation (6).

$$(dx^2/dt^2)+\{(J+k1-K\cdot k2|r-Kf|^n)/JT\}\cdot$$
$$(dx/dt)+(K\cdot Kf/JT)x$$
$$=(K/JT)r\ (n=1,\ 2,\ 3,\ \cdots) \qquad (6)$$

Also, the damping coefficient ξ^* of the control

system results in $\xi^* = (J+k1-Kk2|r-K\cdot fx|^n)/2(JT)^{1/2}$. Therefore, when the gains K, k1 and k2 and the desired value r are set so as to meet $J+k1-K\cdot k2\ |r|^n \geqq 0$, the settling time can be reduced. Here, in the section where $J+k1-K\cdot k2\ |r|^n \geqq 0$ is met, the gain k1 is make large, and the gains k1, k2 and K are set with respect to the desired value r such that a value approaches to $J+k1-K\cdot k2\ |r|^n = 0$ as much as possible, so that the settling time is reduced without overshoot, thereby allowing a high speed response.

Thus, according to the above embodiments, by adding a nonlinear inner positive feedback loop to a control system on the basis of the conventional control system, gains and the like are set such that the damping coefficient of the control system meets a positive relationship regardless of the controlled variable, the speed output or the like of the controlled system 1, so that the settling time can largely be reduced without overshoot and a high speed response can be attained.

As set forth above, according to the present invention, a settling time can largely be reduced without overshoot and a high speed response can be realized.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to

the specific details and representative embodiments shown and described herein. Accordingly, various modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.